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Application of Dynamic Programming in Planning Costs of Telecommunication Security Operations to Provide Aid to Civilian Authorities

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The problem in planning costs of an operation, i.e., the problem of determining an optimal capacity of units used in time is a highly complex problem whose solution can be obtained in different ways, depending on what is taken as an optimality criterion and the types of limiting factors that are present during an operation's realization. The main goal of this paper is to show the practical application of dynamic programming with the aim of improving planning and organizing forces and costs during the realization of the Serbian army's third mission. Data on the use of Serbian Military's units after the earthquake in the area of Kraljevo in 2010 were analysed. The paper covers the use of dynamic programming, namely, the complex optimization problem of using military units, which depends on a large number of variables and can be extremely difficult to solve, is disassembled into several smaller partial problems that depend on one variable and are simpler to solve. The model of using the military is based on mission usage and represented as one of possible scenarios of natural disasters that engulfed a part of the Serbian territory.

Keywords: dynamic programming, telecommunication security, costs, operation to provide aid to civilian authorities.

1. Introduction

The use of the military in aiding civilian authorities represents a mission declared in the doctrinal documents of the Republic of Serbia. Its use in such situations (Sahin et al., 2008) is directly linked to consequences of natural and other types of disasters (Breckner et al., 2016) that threaten citizens and material goods.

The context of aiding civilian authorities in rehabilitating consequences caused by natural disasters (Baker, 2014) includes various areas. One such area is telecommunications. The key moment represents re-establishing an impaired communications system in a territory's region and the possibility of establishing communication flows so they can assist the military (Sheu & Pan, 2015).

The paper highlights a segment through which the model of dynamic programming in the process of planning costs (Elshqeirat et al., 2013) of telecommunication support (Czajkowski & Sobolewski, 2016) is explained. This support includes the area affected by earthquakes of catastrophic magnitude. This model is based on the data on the use of the Serbian Military units in the area of the Raška district in 2010.

The Law on Emergency Situations (2009) defines the role of the military in such situations while the Law on Defence (2007) and the Law on the Army of the Republic of Serbia (2007) defines the use of the Army of Serbia in the implementation of operations for supporting civilian authorities in case of natural disasters. Also, the planning, preparation and execution of operations employ many subsystems of the country whose performance depends on the ability to achieve defined goals (Stanković, 2013).

Considering these regularities, it is possible to predict the future variations of human, financial and material resources that should be available in certain periods. For those needs, it is necessary to analyse the data on hiring the Serbian army in the accomplishments of similar assignments. This paper's contribution is in defining models of projecting necessary forces intended for supporting civilian authorities in case of natural disasters (Sodhi, 2016), by applying dynamic programming (Zhu et al., 2015).

This paper is motivated by the work of Pavlovic & Karovic (2015). They analysed the application of Bass's diffusion model in forecasting the number of users of telecommunication services in an event of a natural disaster. Assistance to civilian authorities in mitigating consequences caused by natural disasters includes various actions. One such action is supporting telecommunication systems. The key issue is the restoration of broken communication systems within the affected regional location and the ability to re-establish the system with the assistance and engagement of the military's units.

2. Literature Review

Richard E. Bellman (Bellman, 1954) was the first to define dynamic programming as a method of operational research for optimisation of multistage and multiphase processes. There are significant differences when applying methods of dynamic programming in relation to a majority of mathematical methods, especially linear programming. The main and basic difference is that in the application of dynamic programming there are no universal methods and corresponding algorithms (such as simplex method in linear programming or CPM and PERT methods in network programming) whose application can solve a majority of problems in dynamic programming. Unlike universal methods, a special and specific approach is necessary for solving almost all practical problems with the application of dynamic programming which is a multistage i.e., multiphase method (Backovic et al., 2014).

The application of dynamic programming in determining the capacity is presented in the work of (Wang & 2017) who propose a solution to decision-making related to (i) technology replacement policy and (ii) a capacity to plan resources for satisfying customer demands under technological changes. Here dynamic programming is primarily used for simultaneous capacity planning.

Certain authors (Ferreira et al., 2016) propose a stochastic approach based on dynamic programming to mitigate adverse climate change impacts and to increase the adaptive capacity of forest stands. This approach is the more innovative as it fully integrates a stochastic dynamic approach with a process-based model that is sensitive to climate parameters.

Application of dynamic programming in the area of natural disasters takes several years into account (Li et al., 2012). Lim (Lim et al., 2016) proposes to prioritize the evacuation based on the danger level in the impact areas during a hurricane landfall using dynamic programming. Here the authors triy to find a set of hurricane evacuation zones that enable prioritized evacuation based on the danger level of each area.

Some authors (Paul & MacDonald, 2016) applied historical hurricane data to model storm-related uncertainty. Their paper develops a stochastic optimization model to determine the stockpile location and capacities of medical supplies for improved disaster preparedness in the event of a hurricane. The application of dynamic programming incorporates facility damage and casualty losses, based upon their severity levels and remaining survivability time, as a function of time variant changes in hurricane conditions.

(Rettke et al., 2016) formulated a Markov decision process (MDP) model to examine a military medical evacuation dispatching problem. They employed approximate dynamic programming (ADP) techniques to obtain high quality dispatch policies relative to current practices.

The analysed available literature shows the application of dynamic programming in circumstances similar to the conducted research. However, the limitation relates to the fact that there is no research that has optimized the engagement of defence system's forces in aiding civilian authorities with dynamic programming.

3. Methodology

The last strong earthquake in the Republic of Serbia was in the area of Kraljevo on the 3rd of November in 2010, with the epicentre in the village of Sirca, and with the magnitude of 5.4 on the Richter scale. The "Report" (2010) stated that after the main shock, a series of aftershocks were recorded, where the magnitude varied from 1.0 to 4.4 units on the Richter scale.

Based on the data of damage caused to buildings and roads, as well as data on the number of injured, measures were taken to provide assistance to people by the Serbian Military as auxiliary forces. It was necessary to consider the type and the extent of used units' costs, for the purpose of the research. We analysed ten units of the Serbian Military employed in the activities of telecommunication security (Gürkaynak et al., 2014). The time interval of the analysis was from the 3rd of November until the 30th of November, 2010.

Disregarding other activities, telecommunication security (Steenbruggen et al., 2013) on the territory affected by consequences after the earthquake will be considered. The realization of this function required securing adequate supplies of modern communication devices to units. All costs occurred in the aforementioned period are shown in the table (Table 1).

Table 1: Costs incurred in the observed period (calculation by the author)

Costs	Account no.	Percentage
Field work	4221	12%
Fuel and lubricants	4264	11%
Food articles	4268	26%
Transport from leasing	4229	7%
Current repairs and equipment maintenance	4252	44%

Costs and expenditure in the Serbian Defence system are categorized as: 1) personal; 2) operating and 3) expenses for investment. Based on the data, it can be concluded that the most represented type is operating costs which amount to 88% in this case. Within these, "current repairs and equipment maintenance" are dominant with almost 50% of total incurred costs.
From the structure of costs that units had in the observed period, it is clear that costs of maintaining telecommunication equipment and network are highest.

3.1. Analysis of the model of dynamic programming

The aim of making the optimum expenses model of telecommunication security in operations of assisting civilian authorities in case of natural disasters by using dynamic programming (Bertsekas, 2012) is to point to the possibility of determining the capacity of units for telecommunication security that should be used, and optimization of usage costs depending on the extent of disaster consequences.

The problem is complex because it is necessary to determine the optimal unit capacity and costs of their engagement for the entire planned period *T*, comprised of several time intervals or units.

$$t = 1, 2, ..., T$$

which can be solved by applying different methods and models of dynamic programming (Davis et al., 2016).

Let us say that during the planned period which comprises four intervals (Miltenburg et al., 1990) $t = 1, 2, ..., T$, $T = 4$ Q units are used, and if the number of users of telecommunication devices is known in each interval $w_t, t = 1, 2, ..., T$ is derived based on the number of citizens that live in the observed area. The costs of using units in the predicted capacity $v_t, t = 1, 2, ..., T$ were also projected, which can be assigned in different ways depending on the size of units in each time interval of the given planned period *T*.

In these kinds of problems of planning units used in time, the capacity of a used unit in each time interval appears as a limiting factor, depending on the capacity of units foreseen for response, their equipment, training and the like. Not all of the factors will be analysed for the purpose of making the model, but the maximum possible capacity that can be used in each unit of time will be assumed. The minimum capacity can be set up as a second limiting factor, because the units are formed from permanent members and means which are already in use.

If *Z* marks units with the size *Q*, formed in the *T-1*-time unit, which will be used in the *T* time unit, then it will be necessary to use in this time the unit exactly

$$v_t = w_t - Z, units\, Q \tag{1}$$

if we assume the expenses of using the units are $g_t, t = 1, 2, ..., T$, which include costs of: field work, fuel and lubricants, food articles and transport from lease, current repair and maintenance, known through each time interval. Relatively fixed costs can appear at any time, even when the unit is not used, i.e., when it is in standby mode in the field, i.e., in case when the number of users of telecommunication devices does not grow, but when currently used units are more than sufficient to appease the endangered, which can be shown in the following way

$$v_t > w_t, t = 1, 2, ..., T \,, \tag{2}$$

where $v_t, t = 1, 2, ..., T$ marks the capacity of the unit in time unit *t*, which needs to be determined, and w_t the number of users of telecommunication devices. These expenses can be represented as

$$Y(v_t - w_t), t = 1, 2, ..., T \tag{3}$$

in the observed case this will be represented by a linear function, because even this type of expense moved with linear progression in the research.

There are also limitations in regard to the maximum possible capacity of a unit, as well as a minimum capacity in each time interval. If $C_t, t = 1, 2, ..., T$ represents a maximum possible capacity of a unit and $c_t, t = 1, 2, ..., T$ a mandatory or minimum capacity of units (maximum and minimum capacities of units represent a certain number of users of telecommunication devices which a unit can service) in each time unit of a period *T*, then a limitation can be set up (Powell, 2010)

$$c_t \le v_t \le C_t, t = 1, 2, ..., T \tag{4}$$

or limits

$$v_t \ge c_t \; and \; v_t \le C_t, t = 1, 2, ..., T \tag{5}$$

The data on maximum possible capacity of a unit C_t, and minimum capacity of a unit c_t for each time interval ($t = 1, 2, ..., 4$) are derived based on the research of the elements of forces level of preparedness and the ability to form twenty units from the previous research.

A third group of costs is related to maintenance of telecommunication devices and a telecommunication network. This means that in some certain time units, the process of performing an operation can be found in such a state that Serbian Military's units which perform operations are not adequately equipped with necessary resources. In that case units must perform emergency procurement of necessary resources which creates additional costs i.e., when

$$w_t > v_t, \; t = 1, 2, ..., T \tag{6}$$

these costs can be analytically represented by the function

$$Y_1(w_t - v_t), t = 1, 2, ..., T \tag{7}$$

Costs of emergency procurements can be presented using a quadratic function in the observed case, because we have shown that they account to 50% of total costs.

In each time unit of the observed process of performing an operation, there are two different possibilities of planning operation costs which are: using a unit to service telecommunication devise w_t users, which will cause an emergence of relatively fixed costs and usage costs that need to be minimised, which can be written in the form

$$\min\left\{Y(Z-w_T+v_T)+g_Tv_T\right\}, \tag{8}$$

with limitations:

$$v_T \geq w_T - Z \tag{9}$$

$$c_T \leq v_T \leq C_T \tag{10}$$

where

v_T - unit capacity;

c_T - minimum unit capacity;

C_T - maximum unit capacity;

Z – Size of a unit formed in previous time intervals, which will be used in *T* time unit.

If the destruction of a telecommunication network is vast, the costs of maintaining telecommunication devices and a telecommunication network and the costs of usage that need to be minimized will appear. This can be shown in the following expression

$$\min\left\{Y_1(w_T-Z-v_T)+g_Tv_T\right\} \tag{11}$$

with limitations

$$v_T \leq w_T - Z, \tag{12}$$

$$c_T \leq v_T \leq C_T \tag{13}$$

The function with which total expenses in T time unit are minimized and can be written in the form (Vuleta at all, 1996)

$$y_T(Z)=\min\begin{Bmatrix}\min\left\{Y(Z-v_T+w_T)+g_Tv_T\right\}\\ v_T\geq w_T-Z\\ \min\left\{Y_1(w_T-Z-v_T)+g_Tv_T\right\}\\ v_T\leq w_T-Z\end{Bmatrix}, \tag{14}$$

with limitation

$$c_T \leq v_T \leq C_T$$

Based on the derived function, it is necessary to establish patterns $y_t(Z)$, for $t=T-1, T-2, ..., 2$ with which total expenses in *T-1, T-2*, until the first time unit are minimized, where the procedure ends with determining $y_1(Z)$ for $Z=0$.

For *t* time unit the pattern can be written as

$$y_t(Z) = \begin{cases} \min\{Y(Z - w_t + v_t) + g_t v_t + Y_{t+1}(Z + v_t - w_t)\} \\ v_t \geq w_t - Z \\ \min\{Y_1(w_t - Z - v_t) + g_t v_t + Y_{t-1}(0)\} \\ v_t \leq w_t - Z \end{cases} \quad (15)$$

with limitation

$$c_T \leq v_T \leq C_T$$

From the mentioned relation a conclusion can be derived that for the case in which costs of maintaining telecommunication devices and telecommunication network exist, in the pattern for determining total minimal expenses for expenses in the following period $y_{t+1}(Z)$, only expenses for *Z =0* are taken into consideration. This is because *Z* represents the capacity of the unit formed in previous and used in the observed time unit. However, seeing that there are relatively fixed costs in the time unit *t*, *Z =0* capacity of the given unit will be transferred into the following time unit *t*+1, thus only corresponding expenses for *Z =0*, i.e., $y_{t+1}(0)$ are present in the relation.

4. Preliminary Data Analysis

For the purpose of practical use of this model, based on the conducted research and the aforementioned, a following assumption can be set. In the Kraljevo region, the administrative district of Raška, an earthquake with the magnitude of 6.5 degrees on the Richter scale occurred, causing vast material damage with a large number of injured and killed (a rather large earthquake – can cause damage in an area of 160 km in populated areas). This type of earthquake is characterized by aftershocks which can cause additional damage and take a death toll. Serbian Military units were deployed to provide assistance as auxiliary forces, where they executed their functions based on the capacity of forces and resources from which they were composed. The time period of the operation was twenty days and it was divided into four intervals for the needs of the model. The model based on division of the territory can be applied in a particular number of areas in accordance with the intensity of the natural disaster's negative effects.

A successful realization of operations for supporting civilian authorities in case of natural disasters requires that units should be equipped with modern telecommunications facilities. Radio transceivers in the VHF frequency range for communications over shorter distances, and HF frequency range for communication over longer distances will be used in a unit with the brigade command-staff. (Pavlovic & Karovic, 2015)

Based on previously conducted research of the twenty units that participated in assisting civilian authorities after the earthquake in the region of Kraljevo, the model represented the value of all variable inputs. All of these indicators are shown in Table 2.

Table 2: Variables in the proposed model

t	*t=1*	*t=2*	*t=3*	*t=4*
w_t *(in tens of thousands of citizens)*	8	8	4	7
g_t *(expenses in millions of dinars)*	3	5	8	5
$Y(v_t - w_t)$	$2(v_1 - w_1)$	$2(v_2 - w_2)$	$2(v_3 - w_3)$	$2(v_4 - w_4)$
$Y_1(w_t - v_t)$	$(w_1 - v_1)^2$	$(w_2 - v_2)^2$	$(w_3 - v_3)^2$	$(w_4 - v_4)^2$
C_t *(in tens of thousands of citizens)*	6	6	6	6
c_t *(in tens of thousands of citizens)*	0	3	5	3

It is necessary to determine the optimal amount of telecommunication devices and equipment for units that perform operations for each of the four time intervals, so that total costs, comprising the costs of using telecommunication equipment, relatively fixed costs and costs for maintaining telecommunication devices and telecommunication network should be minimal while satisfying the given limitations.

Solution: If we subtract the value of minimum capacity of used units c_t from the number of telecommunication device users w_t, for each $t = 1, 2, ..., 4$, we will obtain the number of telecommunication service users that are required to provide the unit with missing telecommunication equipment in each time period which, if marked with $w_t^{'}$ amounts to

$$w_t^{'} = (8, 5, -1, 4)$$

while the minimum unit capacity for each time period $t = 1, 2, ..., 4$ is now equal to zero, and costs of minimum capacity, when marked with $y(c_t)$ will be

$$y(c_t) = \sum_{t=1}^{4} g_t c_t = 3 \times 0 + 5 \times 3 + 8 \times 5 + 5 \times 3 = 70$$

The solution to the problem of dynamic programming starts with calculating the minimal value of the criterion function from the last stage t=4 to the first stage t=1.

All of the obtained results can be represented in the table:

Table 3: Overview of total minimum cost

Z	$y_4(Z)$	v_4	$y_3(Z)$	v_3	$y_2(Z)$	v_2	$y_1(Z)$	v_1
0	14	1 or 2	16	0	35	2 or 3	57	6
1	9	0 or 1	13	0	30	1 or 2		
2	4	0	10	0	25	0 or 1		
3	1	0	9	0	20	0		
4	0	0	10	0	17	0		
5	2	0	14	0	16	0		
6					17	0		
7					20	0		

From this table the minimum costs can be obtained and they amount to 57 million dinars. Based on the results shown in Table 3, total costs for each interval separately can be calculated.

The total minimum costs are obtained when we add costs of compulsory capacity marked with *G* to the minimum costs of 57 million dinars, so they amount to $G = 70 + 57 = 127$ million dinars.

Cost overview per time interval is obtained in the following way:

$y_1(Z) = 57$, for $Z = 0$ and $v_1 = 6$

which means that the capacity of units in the first interval is 60 thousand citizens and corresponding involvement costs will be $g_1 \cdot v_1 = 3 \cdot 6 = 18$ million dinars.
However, the number of endangered in the first interval is 80 thousand citizens, which means that there is a need to spend additional resources to equip the unit, which amounts to

$$(w_1^{'} - v_1)^2 = (8 - 6)^2 = 4$$

Hence, total minimum costs for the first period are 22 million dinars.

If we subtract the minimum total costs of the first interval from the total minimum costs of all intervals, we will obtain the total minimum costs of the remaining five intervals, which amounts to 57 – 22 =35 million dinars.

From Table 4 we can see that

$y_2(Z)=35$ for $Z=0$, v_2 =2 or 3

For the second interval the total minimum costs amount to 19 million dinars and comprise costs for engaging the unit whose capacity is 2, i.e., 3 thousand citizens, which amounts to 10, i.e., 15 million dinars and costs of emergency procurement that amount to 9, i.e., 4 monetary units.

Continuing this procedure of determining the total minimum costs for each interval of hiring a unit, all of the necessary results are obtained, as given in Table 6.

Table 4: Overview of expenses according to time periods

Interval	Capacity of engaged unit	Costs of engagement	Relatively fixed expenses	Expenses of emergency procurements	Total expenses
$t=1$	6	18	-	4	22
$t=2$	2 or 3	10 or 15	-	9 or 4	19
$t=3$	0	-	2	-	2
$t=4$	1 or 2	5 or 10	-	9 or 4	14
TOTAL	9 or 11	33 or 43	2	22-12	57

Output results of the model shown in Table 4 show that costs of maintaining telecommunication devices have a significant share in total costs, which corresponds to the results of the conducted research, the costs of used units in the operation of assisting civilian authorities after the earthquake in the Kraljevo region.

Conslusion

This paper shows the possibility of planning operation telecommunication security costs in assisting civilian authorities in case of natural disasters by using dynamic programming. We stressed the situation that had such proportions that the existing telecommunication infrastructure was not usable. Serbian Military units were used as auxiliary forces in assisting the endangered citizens.

The data analysis of hired units from the defence system in the previous time period is one of the key problems in an inadequate planning of forces and assets for realizing the third mission of the Serbian army. Unfortunately, the practical application of quantitative methods is on a low level. Some of the possible reasons for this situation might be low levels of engineering/mathematical background in the defence system, lack of process-related data for modelling, lack of in-house operations research expertise and high costs of engaging external consultants.

The main goal of this paper is to present and encourage practical application of different quantitative methods for the purpose of improving planning and organizing forces and assets intended for the realization of the third mission. This is among the first papers that used combined quantitative data analysis on engaging the Serbian Army in aiding civilian authorities during natural disasters

The output of the model show that costs of maintaining telecommunication devices and the telecommunication network take the most significant share in the total costs, which corresponds to the results of the conducted research of using units in the operation of assisting civilian authorities after the earthquake in the Kraljevo region. The reason for this is an insufficient number of telecommunication devices and equipment in units used for ensuring telecommunication security and aid to the destroyed infrastructure.

The mentioned model can be used to set standards for corresponding resources and telecommunication equipment for Serbian Military units in order to assist civilian authorities in case of natural disasters, as well as reduce costs that occur during emergency procurement of missing resources.

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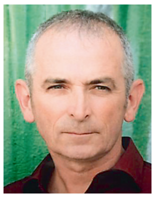

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